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ABSTRACT

The purpose of this study was twofold: (1) to understand the conceptual frameworks that sixth-grade students use to explain the nature and structure of matter and molecules; and (2) to assess the effectiveness of two alternate instructional units in helping students change those conceptions. The study involved 15 sixth-grade classes taught by 12 teachers in each of 2 successive years. Student misconceptions were investigated during the first year. Clinical interviews administered to 24 students and tests administered to 365 students revealed that their thinking about the nature of matter and about physical changes in matter differed from canonical scientific thinking in a number of ways. The main purpose of the second year of the study was to compare the effectiveness of the original commercial teaching unit with revised curriculum materials in promoting student understanding of matter and molecules. Posttest scores for both years were compared. The differences in posttest scores concerning aspects of matter and molecules were statistically significant for 9 of the 10 conceptual categories studied. Implications for science teaching and curriculum development are discussed. Conceptual frameworks, charts of student conceptions and tasks, a copy of the pre/posttest, and the interview protocol and analysis system are appended. (CW/Author)

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Abstract

The purpose of this study was twofold: (a) to understand the conceptual frameworks that sixth-grade students use to explain the nature and structure of matter and molecules, and (b) to assess the effectiveness of two alternate instructional units in helping students change those conceptions. The study involved 15 sixth-grade science classes taught by 12 teachers in each of two successive years.

The main purpose in Year 1 was to understand common student misconceptions about aspects of matter and molecules. Clinical interviews administered to 24 students and tests administered to 365 students revealed that their thinking about the nature of matter and about physical changes in matter differed from canonical scientific thinking in a number of ways. These differences included molecular conceptions concerning the nature, arrangement, and movement of molecules as well as macroscopic conceptions concerning the nature of matter and how it is affected by physical changes.

The main purpose in Year 2 was to compare the effectiveness of the original commercial teaching unit with revised curriculum materials in promoting student understanding of matter and molecules. Posttest scores for both years were compared. To assure that students' ability was comparable across the two years, reading and math scores on the Stanford Achievement Test were also compared, revealing no significant differences. The differences in posttest scores concerning aspects of matter and molecules were statistically significant for 9 of the 10 conceptual categories studied. Implications for science teaching and curriculum development are discussed.

CHANGING MIDDLE SCHOOL STUDENTS' CONCEPTIONS OF MATTER AND MOLECULES

Okhee Lee, David C. Eichinger, Charles W. Anderson, Glenn D. Berkheimer, and Theron D. Blakeslee[1]

Theoretical Basis and Purpose

The purpose of this study was twofold: (a) to understand the conceptual frameworks that sixth-grade students use to explain the nature and structure of matter and how physical changes occur, and (b) to assess the effectiveness of two alternate instructional units in helping students change those conceptions.

Scientists' explanations of the nature of matter and changes in matter depend on the kinetic molecular theory, which states that all matter is composed of tiny particles that are constantly in motion. This theory is an important topic for research on students' conceptions because a correct understanding of the nature and structure of molecules is crucial to understanding much of the physical sciences, chemistry, and the life sciences. The kinetic molecular theory provides the basis for understanding the invisible molecular events underlying natural phenomena as well as for explaining the visible aspects of these same phenomena.

A number of researchers have worked to identify and document students' misconceptions concerning matter and molecules (for example, Ben-Zvi, Eylon, &

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Libbarstein, 1982; Erickson, 1979; Hibbard & Novak, 1975; Novick & Menis, 1976; Novick & Nussbaum, 1978, 1981). In an interview study of eighth-grade students, Novick and Nussbaum (1978) examined students' conceptions of the kinetic molecular theory by having them explain several phenomena dealing with the gaseous phase of matter. Novick and Nussbaum identified several student misconceptions about the theory including the continuous versus the particulate nature of matter; unequal versus equal distribution of gas molecules; the existence of air, dirt, or germs between molecules versus empty space between molecules; and static molecules or the need for an external force to move molecules versus intrinsic molecular motion.

In investigating changes of state, Osborne and Cosgrove (1983) examined students' conceptions about the phenomena of melting, boiling, evaporation, and condensation in a sample of students ranging from 8 to 17 years old. These researchers identified a number of specific misconceptions which were consistently held by students in all age groups. In spite of having received instruction on these topics, many students continued to use their naive conceptions when explaining phenomena. For example, 42% of the students who were asked what bubbles in boiling water were made of said that they were made of air. In addition, when students were shown a sealed glass jar containing melting ice and were asked to explain the origin of the water which had condensed on the outside of the jar, 23% stated that the water came through the glass, while nearly 20% said that the coldness had come through the glass and produced water.

The philosophy of the nature of science and scientific understanding guiding this research differs from more traditional views of the nature of science, and it is based on recent advances in cognitive science and the philosophy of science. According to one traditional view, learning science

involves the mastery of two independent components, content knowledge and science process skills. Based on this view, new knowledge that is generated by the scientific method is simply added to current knowledge. In contrast, the newer view of learning science sees students taking an active role in building new knowledge by modifying their existing conceptions (Posner, Strike, Hewson, & Gertzog, 1982).

The research reported in this paper seeks to add to and expand on this conceptual change tradition in two ways. First, we have tried to develop a more extensive and wide-ranging understanding of students' conceptions of matter and molecules than the understanding of the studies cited above. Second, we have tried to develop an analysis that is consistent with the views of philosophers of science such as Toulmin (1972) and psychologists such as Vygotsky (1962, 1978), who argue that knowledge is fundamentally social, developed and held by communities as well as by individuals within those communities. This has led us to develop a form of analysis that includes both individual and social components (Anderson, & Roth, 1989).

The social or functional component of scientific understanding involves the ability to use scientific knowledge to engage in important social activities: describing, explaining, predicting, or controlling real world systems or events. Students who truly understand science are able to apply their scientific knowledge to the world around them by engaging in the four activities mentioned above.

The individual or structural component of scientific understanding involves developing both an understanding of the interrelationships between various scientific conceptions and between scientific conceptions and one's own prior knowledge. Successful learners of science are able to integrate scientific conceptions and their "commonsense" understandings of the world

around them instead of seeing scientific knowledge and personal knowledge as separate. In addition, scientific understanding requires an understanding of the complex relationships between structure and function. Performing any one of the four functions of science requires the integration of many concepts; likewise, any particular concept can be used for a number of functions (Anderson & Roth, 1989).

This two-level analysis was important for the larger purpose of the research project, which was to develop curriculum materials to teach the kinetic molecular theory to middle school students. The results of our research on student conceptions were used to modify an earlier unit from the Houghton-Mifflin Science program (Berger, Berkheimer, Neuberger, & Lewis, 1979).

Thus, this report also adds to a growing body of research concerned with the effects of teaching strategies and curriculum materials on students' conceptual understanding. Previous research has shown that knowledge gained by identifying and probing into students' existing conceptions of natural phenomena can be incorporated into the development of new curriculum materials designed to promote conceptual understanding. A number of recent studies (Anderson, 1987; Berkheimer, Anderson, & Blakeslee, 1988b; Eaton, Anderson, & Smith, 1984; Roth, 1985; Roth & Anderson, 1987) have shown that these materials can be more effective in promoting meaningful learning for students than more traditional science curriculum materials. These materials incorporate strategies which promote conceptual understanding by getting students actively involved in using scientific knowledge to describe, explain, predict, and control the world around them (Anderson & Roth, 1989; Anderson & Smith, 1987; Blakeslee, Anderson, and Smith, 1987; Minstrell, 1984). Thus, conceptual

understanding and student achievement have been significantly improved by incorporating scientific knowledge with students' existing conceptions and by having students apply their new knowledge in developing explanations for common natural phenomena.

The development process for the new unit, "Matter and Molecules," is described in detail in other papers (Berkheimer et al., 1988b; Berkheimer, Anderson, & Spees, 1990). The unit itself is also available (Berkheimer, Anderson, & Blakeslee, 1988a; Berkheimer, Anderson, Lee, & Blakeslee, 1988). This paper compares student achievement with the original and with the revised units.

Method

Subjects

The study involved 15 sixth-grade science classes taught by 12 teachers in each of two successive years. The classrooms were located in all four middle schools in an urban school district with an ethnically mixed, primarily lower socioeconomic population in the Midwest: 25% black, 10% Hispanic, 3% Asian, 2% American Indian, and 60% white students. Every sixth-grade science teacher in the district participated in the study (16 teachers in Year 1, 14 teachers in Year 2). Teachers who participated in only one year of the study due to changes of assignment were deleted from the sample reported in this paper. All 12 of the teachers who participated in both Year 1 and Year 2 were veteran teachers with previous experience teaching the original Models of Matter unit (Berger et al., 1979). To be representative of the student population in the school district, 12 regular and 3 accelerated classes taught by the same teachers were selected each year.

Four out of the 12 teachers worked closely with the development project as collaborating teachers, one from each of the four schools. One of the major contributions of the four collaborating teachers was to field-test instruments and curriculum materials before they were administered or implemented in the other classrooms (Berkheimer et al., 1988b).

Two kinds of instruments were administered to students each year: paper-and-pencil tests and clinical interviews. The two instruments and the procedures for the administration of them were the same in both years. Four classes taught by the four collaborating teachers were given a paper-and-pencil test prior to instruction. During the first year, 101 students took the pretest; during the second year, 105 students took the pretest. After instruction, all of the 15 classes, including the above four classes, were given the same test. During the first year, 365 students took the posttest; during the second year, 370 students took the posttest.

Twenty-four students from the classes of the four collaborating teachers also participated in clinical interviews both before and after instruction each year, totaling 48 students during the two-year period. These students were selected by their teachers, who were asked to select two students from each of three achievement levels: high, middle, and low.

Curriculum Materials

Two alternative sets of curriculum materials were used during the two years of the study (Berkheimer et al., 1988b). During Year 1, students studied the original Models of Matter unit included in the sixth-grade level of the Houghton Mifflin Science series (Berger et al., 1979). In Year 1 the main purpose was to understand common student misconceptions about aspects of matter and molecules, misconceptions which would be addressed in the revision of

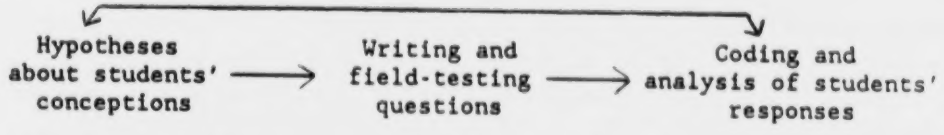
the original unit. During the second year, students studied the revised Matter and Molecules unit developed by the research project team (Berkheimer et al., 1988; Berkheimer et al., 1988a). In Year 2 the main purpose was to compare the effectiveness of the two sets of curriculum materials used in Year 1 and Year 2.

The two sets of instructional materials are different in several respects (see Berkheimer et al., 1988b for details). First, the primary knowledge base of the Models of Matter unit consisted only of canonical scientific knowledge, while the Matter and Molecules unit was also based on the research concerning students' conceptions about the unit content as reported in this paper. Second, in contrast to the Models of Matter unit, which described learning outcomes as a set of interacting concepts and process skills, the Matter and Molecules unit described learning outcomes as a set of conceptual changes which students needed to undergo as they learned to perform scientific tasks. Third, while the Models of Matter unit focused only on molecular conceptions, the Matter and Molecules unit also included a set of macroscopic conceptions concerning the nature of substances and how they are affected by physical changes. Fourth, the Matter and Molecules unit emphasized to students how properties of invisible molecules are associated with properties of observable substances and physical changes. Finally, in order to accomplish these curricular and instructional goals in the Matter and Molecules unit, extensive efforts and resources were invested in the process of developing and field-testing draft materials and a series of revisions. As such, the Matter and Molecules unit was developed with a goal of promoting students' scientific understanding through conceptual change.

Instruments and Data Analyses

Two kinds of instruments were developed, each providing different types of data and each complementing the other. Paper-and-pencil tests were used to gain an overall view of alternative student conceptions regarding aspects of matter and molecules. Clinical interviews were used to provide a deeper understanding of student conceptions and to validate the scoring of the paper-and-pencil tests.

Both the paper-and-pencil tests and clinical interviews were developed using a three-step cycle developed in previous research on conceptual change, as illustrated below (Anderson, Sheldon, & Dubay, in press):


Hypotheses about students' conceptions
Writing and field-testing questions
Coding and analysis of students' responses

In addition to the instruments themselves, we developed a tasks-by-conceptions chart that showed the relationship between the structural (individual) and functional (social) aspects of student understanding and also guided data analysis. The tasks are stated as behavioral objectives calling for students to describe, explain, predict, or control various classes of phenomena, while the conceptions represent the knowledge students are to acquire and integrate. These conceptions can include different types of knowledge (conceptual, procedural, metacognitive, and so forth) that students use to perform scientific tasks.

Appendices B and C present the tasks-by-conceptions chart and the list of conceptions used in our study of the kinetic molecular theory. We identified 19 conceptions related to this theory, some dealing with concepts on the observable or macroscopic level, and others dealing with concepts on the molecular level (see Appendix B). As the chart in Appendix C demonstrates, in

order to successfully perform a particular task, students are required to understand and integrate a number of conceptions. The tasks, therefore, can be thought of as the contexts in which knowledge will be acquired and used. The successful performance of a certain task requires the use of several conceptions, that is, both content knowledge and process skills. In this view of learning science, there is no distinction between these two types of knowledge.

The instruments and data analysis procedures are described below for both the paper-and-pencil tests and the clinical interviews. The reliability among coders for each of the instruments and the reliability between the two instruments are also discussed.

Paper-and-pencil test. Initially, a pool of test items dealing with the kinetic molecular theory was developed based on three major sources: (a) questions dealing with the 12 key ideas of the kinetic molecular theory stated in the Houghton Mifflin Science textbook (see Appendix A), (b) hands-on activities in the Houghton Mifflin Science textbook, and (c) questions used in previous research on the kinetic molecular theory.

Two parallel tests were developed and then pilot tested by a reference group of sixth-grade science students. The effectiveness of individual questions on each test was evaluated according to two major criteria: (a) how well a question elicited responses that revealed alternative student conceptions, and (b) how well a question communicated with students in terms of the clarity of expressions or wording, and in terms of avoiding potential difficulties of interpretation. After carefully examining student responses, questions that met the above two criteria were selected. New items were also developed based on our hypotheses about student conceptions and the parallel work on the clinical interviews (described below). Finally, one test was

constructed which was comprehensive in covering the unit content but short enough to be administered within a 40-50 minute class period.

The test was designed to assess student understanding of a number of key conceptions in the kinetic molecular theory (see Anderson & Smith, 1983; Blakeslee et al., 1987 for more information). The test included 26 questions in multiple-choice and short essay formats (see Appendix D). Some of the questions on the test asked about "knowledge" (e.g., "Have you ever heard of molecules? If you answered yes, what do you think molecules are?"), but the majority of the questions asked for explanations of physical phenomena (e.g., "Explain, in your own words, why heating a solid makes it melt. Explain in terms of molecules of the solid, if you can."). Other questions examined students' ideas about the nature of matter both at the macroscopic level (concerning the nature of substances and their properties) and at the molecular level (concerning molecules and their properties).

After test construction was completed, project staff members administered the tests. During both years, four classes taught by the four collaborating teachers were given the tests prior to receiving instruction on a unit about molecules; all 15 classes were given the tests after instruction. To reiterate, students were taught using the original Models of Matter unit in Year 1, and the revised Matter and Molecules unit in Year 2. No attempt was made to make up tests for students who were absent. Students completed the test within a class period of 45 or 50 minutes.

The coding system to analyze student conceptions was developed after examining student responses on the tests. Originally, the coding system was based on the 12 principles of the kinetic molecular theory stated in the Houghton Mifflin Science textbook (see Appendix A). Student responses on the pilot tests, however, revealed that their learning difficulties were caused by

their misconceptions about observable properties of substances and physical changes as well as their misconceptions about invisible molecules. As a result, the final version of the coding system was designed to assess student understanding of 19 conceptions: eight conceptions at the macroscopic level and 11 conceptions at the molecular level. For each of these 19 conceptions, the scientific goal conception and naive conceptions were identified (see Appendix B).

For each of the 19 conceptions, student responses were coded and tallied across several relevant questions to give a "conception score" that indicated one of three categories: (a) scientific goal conception, (b) ambivalence, or (c) misconception. For each conception, we determined what minimum score constituted adequate understanding of the conception.

Because reporting on 19 different conceptions is unwieldy and hard to follow, and because many of the conceptions are related, we have combined the 19 conceptions into five more general categories, each with a macroscopic and a molecular component. These categories are described in detail in the results section and summarized in Table 1.

Clinical interview. First of all, several major tasks requiring description, prediction, and explanation of natural phenomena were identified. The criterion for the selection of tasks was to develop a minimum number of tasks representing the unit content comprehensively. A structured interview protocol was established, allowing four interviewers to follow a standard procedure. At the same time, to adapt to a variety of student responses and lines of reasoning, branches of probe questions were established throughout the interview protocol. After construction of a draft interview protocol, pilot testing was conducted by a reference group of sixth-grade students. After careful examination of student responses, the final interview protocol was

developed. It included five major tasks: (a) the nature of matter and three states of matter, (b) expansion and compression of gases, (c) changes of state, (d) dissolving, and (e) thermal expansion (see Appendix E). The questions investigated various aspects of students' understanding of matter and molecules at both macroscopic and molecular levels: prediction and description to some extent, and predominantly explanation of natural phenomena.

After completion of the interview protocol, 24 students were interviewed each year. Each student was interviewed prior to and after instruction using the original "Models of Matter" unit in Year 1 and the revised Matter and Molecules unit in Year 2. During the interviews, the students described, explained, and made predictions about real-world phenomena presented by the interviewers. Each interview took about a class period of 45 or 50 minutes with each student. The interviews were tape-recorded and later transcribed.

Student responses were analyzed using the tasks-by-conceptions chart. As a first step, student responses for each example were judged as representing one of the following categories: (a) scientific goal conception, (b) partial understanding of scientific conception, (c) misconception, or (d) ambiguous response. The judgments were coded in the blank cells on the task-by-conception chart (see Appendix F). For each conception, a student's responses across relevant tasks were judged as representing one of the above four categories. Since the main purpose of the clinical interviews was to gain a deeper understanding of student conceptions based on student responses on paper-and-pencil tests, the focus of analysis was on the description of alternative student conceptions for each of 19 issues on the tasks by conceptions chart, rather than any summative, formal analysis.

Reliability. Two issues will be discussed: (a) reliability among coders for each of the two instruments and (b) reliability between the two instruments.

1. Paper-and-pencil test. After the coding system for paper-and-pencil tests was developed, all the staff members tried the system independently on randomly selected tests. When there were disagreements, the coding system was revised. The system was established when there was general consensus among the staff members about the effectiveness of the system. Then, four college undergraduates, whose primary responsibility involved coding student responses on tests, practiced together in a group and then independently. When the level of agreement exceeded 90%, the four coders began to code tests independently. Before they started coding test materials in Year 2, the same four coders practiced again until they reached levels of agreement of above 90%.

2. Clinical interview. The coding system for clinical interviews was developed and tested by the four interviewers, all senior staff members. As the system was being developed, the four interviewers practiced coding in a group as well as independently. When they had reached general consensus about criteria for coding decisions, each interviewer coded responses for the students that he or she had interviewed.

3. Reliability between the two instruments. After coding was completed, the reliability between the two instruments was calculated. Only responses of those students who completed both paper-and-pencil tests and clinical interviews were included. Student responses were analyzed as revealing their level of understanding into one of three categories: (a) scientific goal conception, (b) misconception, and (c) ambiguous response or partial understanding.

The reliability between the two instruments was obtained based on the agreements or disagreements of decisions across each of the 19 conceptions with all 48 students. An agreement was assigned when the two decisions for a conception from the two instruments were congruent, that is, both scientific goal conceptions, both ambiguous, or both misconceptions. Disagreements were assigned to all the other combinations of decisions. The reliability between the two instruments was 73.3%. Considering the fact that analyses were conducted by multiple coders on information collected from multiple sources involving a relatively small number of students, we deemed reliability between the two instruments to be satisfactory.

Results

This section includes two parts. The first part describes common student misconceptions based on student responses in clinical interviews. This part also examines the relative effectiveness of the two instructional units based on student performance on tests and illustrates successful and unsuccessful patterns of student learning with examples from student interviews. The second part presents a more rigorous comparison of the relative effectiveness of the two instructional units based on statistical analysis of student performance on tests.

Part 1: Student Conceptions and Student Learning

In general, student responses for all the 19 conceptions prior to instruction showed that most students had misconceptions at the macroscopic level and did little more than guess at the molecular level. The overall percentage of students who demonstrated adequate understanding of scientific conceptions on paper-and-pencil tests prior to instruction was 3.8% in both Year 1 and Year 2. Student responses after instruction in Year 1 showed that

many students learned to use "molecular" language while retaining some basic misconceptions they had prior to instruction. Overall, the students showed scientific understanding of about 26% of the scientific goal conceptions after instruction in Year 1. The results for Year 2 were better, though still far from perfect. Overall, students demonstrated understanding of 50% of the scientific goal conceptions on the Year 2 posttest.

As described above and in Appendix B, the original analysis focused on 19 conceptual issues, 8 at the macroscopic level and 11 at the molecular level. For the sake of conceptual clarity in our discussion, we recombined those 19 conceptual issues into five general categories, each having a macroscopic and a molecular component. Those five categories serve as the basis for the discussion in this section and they are summarized in Table 1, below. Common student misconceptions are compared with scientific goal conceptions at the macroscopic and molecular levels in each category in Table 1. The table also shows the percentage of students who demonstrated understanding of the scientific goal conceptions on paper-and-pencil tests prior to and after instruction in Year 1 and Year 2. Detailed descriptions of student conceptions in each category are presented below.

Category 1: Nature of matter. The kinetic molecular theory is a theory about both matter and molecules. In order to understand and explain natural phenomena using the kinetic molecular theory, students need to first develop some basic understanding of the nature and structure of matter. The kinetic molecular theory is built around the idea that material substances are made of molecules. But what exactly are material substances? This turns out to be a difficult question for many students. At the macroscopic level, many students either were not familiar with matter as a scientific term or defined the term intuitively, often with statements such as "matter is anything you can feel or

you can see." These intuitive definitions often proved troublesome, since, for example, many students believed that they could not feel air, but they could feel heat.

The conventional textbook definition, "matter is anything that has weight (or mass) and takes up space," was of little help to most students. They generally believed gases such as air, helium, and the smell of popcorn to be weightless. Conversely, they often believed that forms of energy such as light, heat, and electricity take up space. In general, it appeared that many students saw the world as consisting of solids, liquids, and various kinds of ephemeral "stuff," including gases and various forms of energy. Many students were not at all clear about what scientists consider the critical distinction between gases--such as air and helium--and forms of energy--such as heat and light. These difficulties do not automatically resolve themselves as students mature. Hesse and Anderson (1988) observed similar difficulties among high school students in chemistry classes.

The nature of smells was a difficult concept for most students. They did not classify smells as solids, liquids, or gases, but usually listed them as "other." Many students also believed that smells were not really matter, but usually made of "odors," "fumes," or something ephemeral.

Another common misconception concerned the conservation of matter during physical changes. Although this issue will be discussed in several other places with more specific examples, three common patterns of misconceptions seem to emerge: (a) substances are conserved during physical changes, but not necessarily mass, (b) substances transform into other substances during physical changes, rather than simply changing form, and (c) substances disappear and cease to exist, instead of continuing to exist but becoming invisible. Student misconceptions about conservation of matter were a

Table 1: Students' Misconceptions about Aspects of Kinetic Molecular Theory

CATEGORY	MACROSCOPIC						MOLECULAR					
	Contrast		Comparison (%)*				Contrast		Comparison (%)*			
			Yr 1		Yr 2				Yr 1		Yr 2	
			Pre	Post	Pre	Post			Pre	Post	Pre	Post
1. Nature of matter	Goal: Solids, liquids, and gases (including smells) are matter and take up space; Other things (e.g., heat, light) are not matter and do not take up space. Matter is conserved in all physical changes.	Naive: Classification is based on irrelevant properties (e.g., something you can see or feel). Gases and non-matter are incorrectly classified. Transformations conserve substances but not necessarily mass. Substances are transformed during physical changes (e.g., water to air, air to water). Substances disappear and cease to exist.	4.3	20.9	5.0	46.6	Goal: All matter is made of submicroscopic particles or invisible molecules. Molecules are constantly moving and have nothing but empty spaces between them.	Naive: No molecular notion initially. In learning about molecules, non-matter is described as molecular (e.g., heat molecules). Molecules are in substances. Molecules may be comparable in size to dust specks, cells, germs, etc. Molecules may sometimes be still (especially in solids) or move by external forces.	6.0	35.6	5.4	62.1
2. States of matter	Goal: Gases can be compressed, and spread evenly through the spaces they occupy.	Naive: Gases move from one place to another when compressed or expanded, and are unevenly distributed.	3.0	21.1	3.8	49.6	Goal: The three states of matter are differentiated based on the arrangement and motion of molecules in each state. Molecular motion continues independently of observable movement of substances.	Naive: States of matter are differentiated based on observable properties only (e.g., solids are heavy). Observable properties of the state are attributed to the molecules themselves (e.g., molecules are hard in solids), or molecules share in observable properties (e.g., molecules move in gases and liquids, but not in solids.)	2.5	27.3	1.9	52.7

CATEGORY	MACROSCOPIC						MOLECULAR					
	Contrast		Comparison (%)*				Contrast		Comparison (%)*			
			Yr 1		Yr 2				Yr 1		Yr 2	
			Pre	Post	Pre	Post			Pre	Post	Pre	Post
3. Thermal expansion	Goal: Substances expand when heated.	Naive: Substances (especially solids) "shrivel up" when heated; expansion of gases is explained in terms of movement of air (e.g., hot air rises).	10.9	67.7	17.9	79.7	Goal: When a substance is heated, molecules move faster and farther apart.	Naive: Molecules themselves are changed by heating (e.g., molecules become hot, or molecules expand). No relationship between molecules moving faster and farther apart.	3.0	36.2	1.4	58.0
4. Dissolving	Goal: The solute changes from a visible to an invisible form during dissolving.	Naive: The solute "disappears", "melts:, or "evaporates".	9.9	21.4	7.5	66.5	Goal: Molecules of solute break away and mix with molecules of solvent.	Naive: No molecular notion initially. Focus on observable substances, or molecules themselves "dissolve."	1.0	19.5	1.9	58.1
5. Changes of states of matter	Goal: Air contains invisible water vapor, and water vapor in air condenses on cold objects.	Naive: No recognition of water vapor in air, or liquid water changes into air, and vice versa. Condensation is a reaction between heat and coldness.	2.0	5.8	0.5	30.8	Goal: Heating and cooling make molecules of substances move faster or slower, causing changes of state in terms of their arrangements and motion.	Naive: Heating and cooling make molecules themselves change (e.g., molecules "boil", "evaporate"), or molecules share in observable properties of substances (e.g., molecules begin to move when heated.)	3.0	27.8	1.2	41.4

recurring problem and presented difficulties for students in describing and explaining a number of phenomena.

Student performance on paper-and-pencil tests prior to instruction in both years showed that only a small number of students understood the nature of matter at the macroscopic level: 4.3% in Year 1 and 5% in Year 2. Many students had difficulties even after instruction in Year 1; only 20.9% of the students demonstrated scientific understanding. For instance, after learning about the term "matter" and its definition, some students thought that "Everything is matter, whatever exists," including forms of energy such as light, heat, and electricity. They further reasoned that these forms of energy were not solids, liquids, or gases, but "different forms of matter." In Year 2, 46.6% of the students urderstood scientific conceptions of the nature of matter after instruction as demonstrated, for instance, in the following interchange between the interviewer (I) and a student (S):

I: Can you think of any way that those three things (air, water, and rock) are similar?
S: They've both got molecules, um . . . They're both matter, and they both weigh . . . they have weight. They take up space.
I: What do you mean when you say the word matter? What does that mean?
S: You can feel it, you can see it, um, wait . . . it takes up space, and it has weight.

I: If you keep boiling water, does anything happen to the amount of water?
S: It will go down . . . It turns into water vapor and then it kind of evaporates.
I: When it evaporates, is it completely gone or does it stay somewhere?
S: It stays in the air.

At the molecular level, many sixth graders had never heard of molecules before a unit on molecules was taught. Many students had no idea about what substances are made of. When students were asked what substances might look

like at the sub-microscopic level, many students explained in terms of observable properties:

> S: [In the air] there are little specks of dust . . . raindrops or something. Little things, fleas . . . Dirt, um, dirt can be little stones and stuff. That is about it . . . . [In the water] Oxygen. Maybe ice . . . if it melts, it turns into water . . . [In the rock] there are sand and dirt.

Even those who had some knowledge about molecules prior to instruction usually had incorrect ideas about the nature and properties of molecules, such as what molecules are, where they are found, how they move, how big they are, and so on. Even after instruction, many students in Year 1 and some in Year 2 still held misconceptions. Students who were unable to distinguish matter from nonmatter often failed to describe examples of matter as being composed of molecules, while others believed that some forms of nonmatter were composed of molecules (e.g., heat molecules).

Of the students who had some knowledge about what molecules are, many showed various kinds of misconceptions. First, many students believed that molecules are <u>in</u> substances rather than that the substances are composed only of molecules. Students thought that water, for instance, contains molecules like blueberries in a muffin rather than consisting of water molecules and nothing else:

> S: They [molecules] are little particles. They are in most things. Well, they are in everything.

> S: Germs and molecules float in the air.

Second, many students thought that in addition to molecules, there are other things in substances:

> S: [In the air] there are molecules . . . Gases, fumes or something like that . . . and moisture . . . [In the water] there are molecules [represented by big dots] and air [represented by small dots] . . . [In the rock] there are molecules only.

Finally, some believed that molecules were animate:

S: Molecules are tiny organisms that live in the air, and they just are always moving around to stay alive.

S: If it weren't for molecules, everybody wouldn't be alive right now.

Students who believed that molecules are <u>in</u> substances also believed that there can be something else between the molecules, as opposed to the scientific conception that there is empty space between molecules.

S: Well, yeah, there's space, but there's got to be something in it. I mean you don't see open spaces in water.

Then, what is between the molecules of substances? First, some students, especially those who thought that there are other things in substances in addition to molecules, believed that there are different kinds of "stuff" between molecules of substances in different states:

S: [In the air] there is air between the molecules . . . [later changed into] gases, just gases that make up the air . . . [in the water] there is nothing between molecules or air . . . [in the rock] there is dirt between molecules.

Second, some students thought that the same substance exists between the molecules of a substance:

I: We'll talk about the water after we talk about the air.
S: The liquid is between the molecules. The water is in between the molecules.
I: Is there anything in the space between these molecules [in the air]?
S: Air.
I: Is there anything in between the molecules [in the rock]?
S: Rock.

Finally, others thought that there is a "generic" kind of air or air molecules between the molecules in air, water, or rock:

I: Is there anything in that space between the molecules [in the water]?

S: Air.
I: Would there be anything between the molecules of rock?
S: Um, air.
I: Would there be anything in between these molecules [in the air]?
S: Air.

A number of students also had misconceptions about the size of molecules, perhaps because students rarely, if ever, talk or think about things which are as small as molecules. Although students usually thought of molecules as small, it was hard for them to understand how small they really are. Many students thought of molecules as comparable in size to other tiny objects with which they were familiar, such as specks of dust, bacteria, or cells:

S: They [molecules and dust specks] are both about the same size. A speck of dust is three times bigger than molecules.

Students who said that molecules are smaller or much smaller than these objects still believed they could see molecules with a microscope or "magnifying lenses." Even after the revised Matter and Molecules unit emphasized that molecules are too small to be seen even with the most powerful microscope, some students, when asked if they could see molecules with a microscope, said, "Probably, maybe a little bit. Not much," or "I think so, yeah, barely."

Students had difficulty understanding that molecules are constantly moving. Some students thought that molecules may sometimes be still, especially in solids, where no motion of the substance is visible:

I: In the rock, do you think the molecules would be moving?
S: Just a little bit, I'm not sure. Yes, probably, just a little bit.
I: Would they ever stop moving?
S: I don't know, maybe a few times, or sometimes.

S: The rock is a very solid form, and it doesn't have any moving molecules in it until it's like broken.

Others thought that molecules begin to move when external forces are applied:

S: Molecules in the air are moving, because the wind blew them.

I: Would the molecules be moving in the water [in a cup]?
S: Yes, like, if you moved the water, the stuff [molecules] inside of it will move.
I: And what happens if the water is still?
S: They might probably just move a little bit.

Thus, the constant motion of molecules is difficult for students to believe, both because it seems to contradict the evidence of their senses and because they have never encountered objects that, like molecules, are so tiny that they are unaffected by friction and thus never come to a stop.

At the molecular level, student performance on paper-and-pencil tests showed that only a few students correctly understood the nature, size, or motion of molecules prior to instruction: 6% in Year 1 and 5.4% in Year 2. After instruction 35.6% of students in Year 1 and 62.1% of students in Year 2 demonstrated adequate understanding of scientific conceptions. Some of the scientific responses given by students after instruction in Year 2 were as follows:

S: Well, molecules are tiny, and they are always moving, and the molecules are the things that make up stuff.

S: It [a molecule] is the tiniest part of a substance.

I: How big are molecules?
S: Molecules are about a trillion times smaller than a speck of dust.
I: Can you see molecules?
S: Nope.
I: How about through a very powerful microscope?
S: They are still too small.

I: Would they [molecules] ever stop moving?
S: No.
I: Say, this week it got down to 15° below zero. Would the molecules of air still be moving at 15° below zero?

S: Yeah, they never stop.

I: Do you think there is anything between molecules [of the rock] here?
S: Space.
I: OK. Is there anything in the space?
S: No.
I: Nothing, so is it empty?
S: Yeah.

Category 2: States of matter. When students were asked to describe the three states of matter at the macroscopic level, they often described them in terms of observable properties, such as, solids are hard and heavy, liquids are wet and runny, and gases are invisible and light. Rarely did they talk about three states of matter at the microscopic level. This is not surprising, at least prior to instruction, considering the fact that few students had ever heard of molecules. Even after the unit was taught, however, many students in Year 1 and some in Year 2 still had difficulty understanding the scientific conception: In solids, the molecules are locked in a rigid pattern and vibrate in place; in liquids, the molecules slide and bump past each other; and in gases, the molecules move freely with much more space between them than in the liquid or solid states.

One of the major difficulties for students was their confusion between observable properties of substances and properties of molecules. For instance, some students attributed observable properties of states to molecules themselves:

S: Molecules are frozen in ice, because they are solid together.
S: The ice is cold . . . the ice molecules would be colder than the ones in the water.
S: Molecules are hard [in rock] because they're all packed together.

Student performance on paper-and-pencil tests at the molecular level showed that very few students had scientific understanding of the states of

matter prior to instruction: about 2.5% in Year 1 and 1.9% in Year 2. After instruction, 27.3% of the students in Year 1 and 52.7% of the students in Year 2 could give scientific explanations. The following excerpt comes from an interview with one such student in Year 2:

I: Now you have three drawings [made by the student and representing molecules of air, water, and rock] in front of you. Could you tell me the differences among these three drawings?
S: Well, in air the molecules move freely and farther apart. In water they are closer together in a pattern but it is not rigid and they move still. In the rock, it's a rigid pattern and they vibrate in their own space.
I: Do you think that molecules are moving all the time and never stop, or is there any occasion when molecules may stop moving?
S: They are always moving.
I: Well, how about in ice?
S: In ice, the molecules are vibrating in their own place like in the rock, a solid.

As opposed to the scientific conception that gases can be compressed or expanded and spread out evenly, students believed that air flows like water from one place to another and, thus, is unevenly distributed. (Unlike all the other information presented in this paper, the following data for compression and expansion of gases are based on student responses at both <u>macroscopic</u> and <u>molecular</u> levels.) For instance, when air is compressed in a syringe, some students thought that air was pushed forward and moved to the opening of the syringe:

S: Because the air is all bunched up together. The plunger is pushing the air forward.

Similarly, when the plunger was pulled back, they thought air was pulled back and concentrated around the plunger:

S: You're pushing it in and then when you bring it out, it's all moving because it's all going back into place. It is moving because of the force.

These students applied the same reasoning to the properties of molecules, that is, air molecules moving from one place to another:

> S: Because the molecules are all pushed up in here because they don't have anywhere to go out so they go down there [opening of the syringe].

Some others explained compression and distribution of air anthropomorphically:

> S: Well, the molecules want to get out and be free, so they're pushing and you're pushing off, so they just go to one place until you let it go.

In attempting to explain why gases are compressible and liquids are not, students often focused on observable differences between air and water. For example, some students said that they were unable to compress water in a syringe because water is "harder" or "heavier" than air, water has more "stuff" in it, or "water takes up more room."

Some students applied the same macroscopic misconception to properties of molecules:

> S: Molecules are different. So they act differently and when you press down on air, they go down because there's not . . . The water is kind of heavy and it would also stop the syringe, and the air isn't heavy so the syringe would go down until the molecules got bunched up.

Even students who understood that there was much more space between molecules of gases versus liquids often got the details wrong. For instance, some students thought that there is no space between molecules in water:

> S: Because water doesn't have anything in between the particles and air does. With water, there is no space to push . . . In air, there is something between the particles, air or something, and you can move a little ways. And there is no space to move in here [water].

Explaining the difference between compression of gases and compression of liquids was a difficult task for many students. A very small number of

students had adequate understanding of scientific conceptions (at the microscopic and macroscopic levels combined) prior to instruction--3% in Year 1 and 3.8% in Year 2. Even after instruction, only 21.1% of students in Year 1 demonstrated conceptual understanding. In contrast, 49.6% of students in Year 2 demonstrated understanding of scientific conceptions after instruction.

I: How would you compare air before you pushed on the plunger and after you pushed on the plunger with air in it [the syringe]?
S: Before, they are just all over in the syringe, not in any special pattern or anything. Now, after, they are close together, they are packed in close together.
I: Do you think there are more molecules in one place than in another, or are they just spread apart?
S: They are spread apart in their own space and they are close together, so they are spread apart in there as much as they can be. I think they are spread out about the same.

Category 3: Thermal expansion. The explanation of thermal expansion requires knowledge about properties of molecules. When a substance is heated, the molecules of the substance move faster and, therefore, move farther apart, which causes the substance to expand. In contrast, when a substance is cooled, the molecules move more slowly and move closer together, so the substance contracts.

At the macroscopic level, student predictions and explanations of phenomena involving thermal expansion indicated that they often did not believe that substances expand when heated. For instance, when asked to predict what would happen when a metal ball is heated (thermal expansion of a solid), some students said that a metal ball would "shrink," or "shrivel up," or "it would be smaller. The heat would make it dissolve." They were surprised to observe that the metal ball could no longer be pulled through a close-fitting ring when the ball was heated, indicating that the metal ball, in fact, did get bigger when heated.

Students were also asked to predict what would happen to a balloon on top of a cold bottle when the bottle was warmed up (thermal expansion of a gas). Most students predicted that the balloon would blow up or get larger, but not because of thermal expansion. Instead, they believed that the balloon would blow up because of hot air or heat:

S: The balloon will blow up because the heat will rise and make it blow up. The air is blowing it up because it's rising.

S: I think, like the hot air from holding it in your hands will rise. So, it will fill up the balloon.

S: The heat would take the place of the cold air.

Thus, student responses seemed to indicate that, rather than believing that air had expanded, they believed that air in the bottle moved from the bottom to the top and, therefore, there was hot air (or heat) at the top and cold air at the bottom. This was further confirmed when many students predicted that if the bottle was turned upside down, the balloon would become smaller because "hot air would rise and cold air would go down."

Even though most students did not understand prior to instruction that substances expand when heated (at the macroscopic level correct responses totaled 10.9% in Year 1 and 17.9% in Year 2), this turned out to be one of the easiest concepts for students to learn in both years--67.7% in Year 1 and 79.7% in Year 2. Especially in Year 1, this concept was understood by far more students than any other concept.

If many students understood that substances expand when heated, did they also demonstrate scientific understanding at the molecular level? This did not seem to be true for many students, especially after instruction in Year 1. There seemed to be several major reasons why many students had difficulties giving molecular explanations. Some students used molecular language to

express the same basic misconceptions as those described at the macroscopic level:

> S: When your warm hands touch it [the bottle], the particles will force the cold air particles up into the balloon and then the balloon will be blown up.

Many students were confused between observable properties of substances and properties of molecules, so they attributed changes in substances to changes in molecules themselves. For instance, they thought that the reason why a substance expands is because molecules themselves expand:

> S: It [the balloon] will blow up because the air molecules are expanding and they need more room so it will go into the balloon.

> S: It [the metal ball] wouldn't go through the ring, because the molecules expanded and caused it to get bigger.

Some students also thought that heating makes molecules themselves become warm or hot:

> S: Well, warm air rises, and warming up the bottle is warming up the air molecules inside, and the molecules are rising up and going into the balloon.

> S: Molecules [in air] would be frozen [in the cold bottle], then they would be warmed up and then they try to go out.

Even students who were aware of a relationship between heat and molecular motion often got the details wrong. For instance, some students thought that molecules <u>start</u> to move when a substance is heated, causing the substance to expand:

> S: Because the air particles when you freeze it are still in the bottle when they are frozen. When you warm up the bottle, the molecules is gonna start moving and go up into the balloon, and the balloon is gonna get bigger.

> S: Molecules are not moving before the ball is heated, because they are solid and they are staying that way.

When the ball is heated, they start moving so they can expand.

The comparisons of student performance (at the molecular level) prior to and after instruction between Year 1 and Year 2 are shown in Table 1. Only a small number of students seemed to understand thermal expansion in molecular terms--3% in Year 1 and 1.4% in Year 2. Compared to 36.2% of students after instruction in Year 1, 58% of students in Year 2 demonstrated understanding of scientific conceptions.

I: Would anything happen [when the bottle with the balloon on it is warmed]?
S: The balloon would blow up a little bit.
I: Why would that happen?
S: Because the molecules start moving faster and they go farther apart and need some place to go and if the opening . . . they go everywhere they can, so they go up in the balloon.
I: Which molecules are we talking about?
S: The air molecules.

I: Why can't the ball go through the ring now?
S: Because the heat from the hot plate made the substance expand. It made the molecules move faster, farther apart, making the substance expand.
[Later when the ball cooled down].
I: Why can it go through now?
S: Because the molecules are moving slower and they slow down, so they get closer together.
I: What happens to the ball?
S: The ball gets back to its normal size.

Category 4: Dissolving. Students are familiar with the phenomenon of dissolving in daily life, but explaining the process requires understanding of several key ideas. At the macroscopic level, students must understand that solute is still present in the solution, but that it breaks up into pieces too small to be seen. At the molecular level, students must understand two key ideas. First, molecules of liquid hit the grains or chunks of solid. Second, molecules of solid break away and spread out evenly in the liquid.

At the macroscopic level, some students did not understand conservation of matter during dissolving. They thought that since sugar was not visible when dissolved in water, it no longer existed:

S: I mean, like, it dissolves into, it dissolves into nothing, and just . . . It means it disappears, I guess.
I: Is it gone forever? Is that what you mean by disappears?
S: Yeah.

Others thought that "the sugar kind of evaporates from the water" or "it melted away." Even when they were asked to taste the water in which the sugar had been dissolved, some still insisted that they could not taste sweetness. After instruction in both years, many students understood that when sugar dissolves in water, "it [sugar] stays in the water, but we can't see it."

Students who understood correctly that the solute is still present after it dissolves were often confused in other respects. The process of dissolving occurs through interactions between liquids and solids. Although the key substances are solids that dissolve in liquids, liquids also have an important function in the change. Water, for instance, has a critical role in the dissolving of sugar; water molecules hit the sugar molecules and cause them to break away from the sugar crystals. Major learning difficulties for most students were the fact that they did not understand the interaction between liquids and solids and, accordingly, revealed various kinds of misconceptions. When asked how sugar got out of a tea bag that was dipped into water, many students focused on the interaction between the water and the tea bag rather than the water and the sugar:

S: The water makes the package all wet and sugar starts to come out of the holes in the bag.

S: Because the tea bag feels like paper, it [water] is going to open, just put a hole in the paper.

S: Sugar comes out because the tea bag gets bigger.

Others thought that sugar "somehow" went through the holes of the tea bag:

S: The bag is getting wet, and it's causing it [sugar] to somehow go out and get into there [the water].

S: Sugar soaks through because the bag gets so wet that it can soak through, maybe.

S: When it [sugar] gets wet, it can soak through.

Many others thought that sugar "melted" like ice melting:

S: Sugar is so sweet, so it melts into water.

S: As I put it [sugar] in the water, the sugar sort of started to melt and went through the holes.

Finally, some students, especially those who believed that the sugar melted, thought that solid sugar turns into a liquid, either water or sugar:

S: It [water] gets it [sugar] wet so that the sugar eventually becomes water. I mean sugar eventually melts into the water.

S: Well, it [water] will make it [sugar] into a liquid, because it melts . . . Solid sugar changes into liquid sugar.

Student performance on paper-and-pencil tests prior to instruction showed that a very small number of students gave adequate scientific explanations of dissolving at the macroscopic level: 9.9% in Year 1 and 7.5% in Year 2. Even after instruction, only 21.4% of students in Year 1 demonstrated scientific understanding compared to 66.5% of students in Year 2.

At the molecular level, almost no students gave adequate explanations of dissolving prior to instruction. Even after instruction, many students in Year 1 still did not use molecular language at all. Of those who gave molecular explanations, many used molecular language to express the same basic misconceptions described above at the macroscopic level. For instance, some students thought that water interacted with molecules of the tea bag rather than the molecules of sugar:

S: It [water] spreads out the molecules of the tea bag so that the sugar can come out. The molecules of the tea bag are spread out.

After sugar dissolves in water, sugar molecules are constantly moving and spread out evenly in the water. A majority of students thought that sugar would sink to the bottom of the water in a cup and stay there because "sugar is heavier than water" or "it [sugar] is a solid form," or "sugar molecules are heavier than water molecules." This confusion between observable properties of substances and properties of molecules caused difficulty even for some students who appeared to understand the constant motion of molecules:

I: If we leave the sugar in water for, say, a day, where will the sugar be?
S: It will be everywhere. It will mix up with the water. It will be evenly spread out, it is fresh.
I: If you leave the sugar in water for, say, five days, where will the sugar be?
S: At the bottom, because if it sits there for five days, it'll be just, be too long.

They further reasoned that since the sugar would stay at the bottom, the taste would be different at the top than at the bottom:

S: [Sugar will stay] on the bottom . . . because it hasn't been like stirred up, so it keeps up with water molecules.
I: Do you think there will be any sugar molecules on the top?
S: There may be a couple.

Student performance on paper-and-pencil tests showed that almost no students could give scientific explanations of dissolving at the molecular level prior to instruction--1% in Year 1 and 1.9% in Year 2. Even after instruction in Year 1, only 19.5% of students demonstrated scientific conceptions of dissolving. In contrast, a significantly higher percentage of students (58.1%) could explain dissolving scientifically after instruction in Year 2.

I: Could you explain dissolving in terms of molecules?
S: The water molecules are going around and hitting the sugar molecules.
S: The sugar in the bag is turning into molecules by the water hitting them and then the molecules breaking off of the sugar grains and going out of the holes and out of the bag.
I: If we were to leave this tea bag in there for a while, where would the sugar be in the cup?
S: In the water.
I: Yeah, in the water, but would it be in one place or all over in the cup?
S: Yeah, all over . . . because the sugar molecules are, they are always moving and they just can't sit down at the bottom of the cup. So they have to move, then they mix in the water.

Category 5: Changes of state. A substance changes its state from solid to liquid, from liquid to gas, or vice versa by heating or cooling. At the molecular level, explaining changes of state requires the integration of a complicated set of scientific ideas about the movement and arrangements of molecules. For instance, when ice is heated, molecules move faster, break out of their rigid arrangement, and begin to slide past each other and move more freely than in the solid. These changes in the movement and arrangement of molecules cause ice (solid) to turn into water (liquid). Because this explanation is complicated, many students had extreme difficulties giving adequate or complete explanations of changes of state.

Before students can understand and explain changes of state in molecular terms, they need to understand scientific ideas at the macroscopic level: The form of the substance changes, but not its mass or its basic nature. A majority of students had learning difficulties with the concept of conservation of matter. Lack of understanding of this concept contributed to a number of misunderstandings about a variety of phenomena. Many students were confused about the conservation of matter during melting and freezing. For instance, they thought that when ice changed to water, the water weighed less because

S: Ice is heavier than water.

S: The solid is closer together than water.

S: Ice has more stuff in it than the water.

Even more students were confused about conservation of matter during evaporation, boiling, and condensation, all changes of state that involve invisible gases. Since a substance becomes invisible, they thought that the substance disappears and ceases to exist or changes into another substance. The most common problems involved the existence of invisible water vapor in the air. Typical explanations of evaporation and boiling include the following:

S: What I mean by evaporates is it [the alcohol] turns into air.

S: It [alcohol] goes up into the clouds and stays there until it rains then it comes down.

S: When it [the alcohol] dried up, then it just keeps flowing and flowing until it's just gone. There's nothing left of it. So it's gone. Not, no alcohol.

S: There is air in the bubbles [of boiling water].

S: In the bubbles, there is gas, just plain gas.

S: There are molecules of heat in the bubbles.

Most students had great difficulty explaining where water on the outside of a cold glass comes from. Common misconceptions about condensation include the following:

S: The air out here . . . the air turns into a liquid [water].

S: Water comes from the heat outside and from the cold inside. Heat mixes with the cold and makes the water.

S: Water will seep through the sides [of the glass] somehow.

S: It [water] just appeared there.

In their explanations of changes of state involving gases, many students focused on "air," which might largely be due to their failure to understand the existence of water vapor:

S: Well, air is coming up from the bottom of it [the water] and it's making a bubble at the top. And so it's boiling.

S: The air dried it [the alcohol] out [evaporation].

S: It [the water on the outside of a cold glass] just appears because of the air; it goes and gets to the glass.

Thus, many students did not understand the concept that matter is conserved during all physical changes of state. Instead, they thought that matter was created or destroyed, or changed into another substance. Student performance on paper-and-pencil tests showed that understanding conservation of matter, particularly involving water vapor in air, turned out to be the most difficult of all the macroscopic conceptions for students. Almost no students understood scientific conceptions at the macroscopic level prior to instruction--2% in Year 1 and 0.5% in Year 2. Even after instruction in Year 1, only a small percentage of students (5.8%) demonstrated scientific understanding. Although many students still experienced difficulties after instruction, a significant improvement was shown in Year 2 (30.8%). Some of the scientific explanations given by students at the macroscopic level after instruction in Year 2 were as follows:

S: Water would weigh the same as ice because it is changing from solid to liquid, so it should weigh the same unless it leaks.

I: If you keep boiling water, what will happen to the amount of the water?
S: Get smaller.
I: Where does the water go?
S: It evaporates into the air, goes from water to water vapor.

I: How is the water formed here?
S: Well, it's . . . it's from the water vapor in the air. It forms on the outside of the glass.

At the molecular level, the prevalence of students' misconceptions about water vapor in air seems to be one of the major causes of learning difficulties for understanding and explaining changes of state. Prior to instruction, only a few students could use molecular language in their explanations. Even after instruction of the unit in Year 1, many students did not attempt to explain changes of state in molecular terms. Others used molecular language to express their misconceptions at the macroscopic level:

S: They [molecules of water] are heating up the air. . . Air forms at the bottom and so when the air comes up to the . . . like it's evaporating at the top but it's boiling at the bottom.

S: Because the molecules in the air go down and they like bring it [alcohol] up into the air. The molecules in the air bring the alcohol into the air . . . [evaporation].

S: The molecules of the air met with the cold molecules of this glass and they just form this water stuff [condensation].

Others attributed observable properties of substances to molecules themselves or confused properties of observable substances and properties of molecules during changes of state. For instance, many students thought that when a substance changes its state, molecules share in observable properties of substances or that molecules themselves change:

S: Molecules in ice is hard or frozen . . . Molecules in ice are not moving and start moving when ice melts.

S: [When ice melts] molecules come out. They get to move around.

S: The molecules are being heated up in it [the water], making water boil.

S: Molecules are drying up and going into the air [evaporation].

S: The molecules are condensing.

Even students who understood individual components experienced difficulty integrating those components to give adequate and complete explanations. For instance, while many students left out one or two basic ideas and, thus, failed to give logical and complete explanations, others included one or two incorrect ideas in their explanations which were otherwise correct.

S: When they [molecules] are in the water, they move farther apart, they move faster, and then they turn into air [evaporation].

Student performance on paper-and-pencil tests showed that making explanations of change of state in molecular terms was among the most difficult tasks for many students. Prior to instruction, almost no students could give scientific explanations of changes of state (at the molecular level)--3% in Year 1 and 1.2% in Year 2. Although significantly more students in Year 2 demonstrated understanding after instruction, 41.4% compared to 27.8% in Year 1, many students still had difficulties understanding changes of state in molecular terms. Some students in Year 2 provided elaborate and complete explanations about changes of state at the molecular level:

S: Well, the water molecules are loosing attraction, they're speeding up, changing state. Um, they start from a rigid pattern to slide and bump past each other, change behavior and action [melting].

S: The molecules, well, the heat from the hot plate is heating up the water, and it's making the molecules move faster, they move farther apart, um, lose attraction. And the molecules, when they move faster, they rise and escape from the surface of the water [boiling].

S: The molecules from the surface will move, well the ones that are warmer will escape from the liquid, from the alcohol, and mix with the air . . . Well, since because they're warmer, they're going off the surface, they are just going to come off the surface [evaporation].

S: The water vapor molecules are, they're, once they change into water vapor, it reaches the glass, which is cooler than the, the substance, the water vapor. And it slows down the water vapor molecules and turns the water vapor into water [condensation].

Part 2: Statistical Comparison of Student Achievement

Table 1 and the discussion above show that students in Year 2 consistently did better on the posttests than students in Year 1. The results of those comparisons are shown in Table 2 below.

Since the treatment each year was applied at the class level rather than the individual student level, we compared class means rather than individual student scores. To avoid "double-counting" the teachers who had accelerated as well as regular classes, the three accelerated classes were dropped from the sample. The means on Table 2 (for the 12 regular classes) are, therefore, slightly lower than the means on Table 1 (for the 12 regular and 3 accelerated classes). To assure that student ability was comparable across the two years, we also compared reading and math scores on the Stanford Achievement Test. Comparisons were done by means of a paired, two-tailed t test.

Table 2 compares student posttest scores in Year 1, when the teachers were using the Models of Matter unit from the Houghton-Mifflin Science series (Berger et al., 1979) and Year 2, when the teachers used the revised Matter and Molecules unit (Berkheimer et al., 1988a). Although the achievement test scores revealed no significant differences in student ability, the differences in posttest scores were statistically significant at the .001 level for 9 of the 10 categories, except macroscopic category 3 (i.e., thermal expansion at the macroscopic level). Further, analysis of student performance for each teacher showed that the students of every single teacher did better in Year 2 than in Year 1.

Discussion

Like many studies in the conceptual change tradition, this study reveals how difficult apparently simple learning can be for students and helps us understand something about the nature of those difficulties. The essence of the kinetic molecular theory can be summarized in a single sentence: Matter consists of tiny particles, called molecules, that are constantly in motion.

Although the above sentence seems simple and easily understood to scientifically literate adults, for the sixth-grade students in this study it was fraught with difficulty. Most students did not understand the word matter, for example, and their misunderstanding could not be resolved by a simple definition. For these students, gases such as air and helium seemed to have more in common with forms of energy such as heat and light than with solids and liquids. Other parts of the sentence proved equally troublesome. These students could envision particles as tiny as specks of dust, or cells, but they had a great deal of trouble imagining particles like molecules that were many orders of magnitude tinier yet. The idea that molecules are constantly in motion is also counterintuitive for many students: It seems to contradict the evidence of their senses (no motion is evident in many substances) and their personal experience, in which all moving objects eventually slow down and stop.

In order to appreciate the power of the kinetic molecular theory, students must understand the above statement and more. In particular, they must see that many properties of matter can be explained in terms of the arrangement and motion of molecules, and many physical changes in matter can be explained in terms of changes in molecular arrangement and/or motion. Many students, however, have a great deal of difficulty understanding matter in these terms. They tend instead to describe molecules as having the same properties and undergoing the same changes as observable substances. Thus molecules of stone

Table 2: Comparison of Student Achievement in Year 1 and Year 2

	Description	Posttest Year 1		Posttest Year 2		Comparison	
		Mean*	S.D.*	Mean*	S.D.*	T-Value**	Prob.
Stanford Achievement test scores	SAT reading comprehension	672	18	673	26	0.16	.87
	Macroscopic Conceptions						
Conceptions of Matter and Molecules	1. Nature of matter, conservation of matter	34%	6.5%	76%	9.7%	8.20	<.001
	2. States of matter: Compressibility of gases	20%	9.0%	42%	15.5%	5.02	<.001
	3. Thermal expansion: Substances expand when heated	66%	14.9%	75%	13.6%	1.98	.073
	4. Dissolving: Solute still exists in solution	20%	8.0%	62%	14.8%	9.33	<.001
	5. Changes of state, water vapor in air	5%	3.5%	26%	14.6%	5.70	<.001

	Description	Posttest Year 1		Posttest Year 2		Comparison	
		Mean*	S.D.*	Mean*	S.D.*	T-Value**	Prob.
	SAT total mathematics	677	17	683	23	0.78	.45
	Molecular Conceptions						
	1. Nature of Matter: Size and motion of molecules	31%	12.6%	55%	16.5%	6.19	<.001
	2. States of matter: Arrangement and motion of molecules in solids, liquids, and gases	23%	11.4%	46%	17.8%	6.23	<.001
	3. Thermal expansion: Molecules move faster and farther apart	35%	17.0%	51%	16.3%	4.45	.001
	4. Dissolving: Molecules of solids break off and mix with solvent	15%	12.6%	52%	17.8%	5.22	<.001
	5. Changes of state: Changes in motion lead to rearrangement	29%	9.4%	45%	16.6%	4.72	.001

* Scores reported are means and standard deviations of class means (not individual student scores). Stanford achievement test scores are scale-scores. Percentile equivalents for means are about 61% for reading and 68% for mathematics. Conception scores are percentages of students in a class demonstrating understanding of the conceptions in that category on the posttest.

** Two tailed paired t test, 11 degrees of freedom. Class mean scores for each teacher (n=12) in Year 1 were matched with class mean scores for the same teacher in Year 2.

CATEGORY	MACROSCOPIC						MOLECULAR					
	Contrast		Comparison (%)*				Contrast		Comparison (%)*			
			Yr 1		Yr 2				Yr 1		Yr 2	
			Pre	Post	Pre	Post			Pre	Post	Pre	Post
3. Thermal expansion	Goal: Substances expand when heated.	Naive: Substances (especially solids) "shrivel up" when heated; expansion of gases is explained in terms of movement of air (e.g., hot air rises).	10.9	67.7	17.9	79.7	Goal: When a substance is heated, molecules move faster and farther apart.	Naive: Molecules themselves are changed by heating (e.g., molecules become hot, or molecules expand). No relationship between molecules moving faster and farther apart.	3.0	36.2	1.4	58.0
4. Dissolving	Goal: The solute changes from a visible to an invisible form during dissolving.	Naive: The solute "disappears", "melts", or "evaporates".	9.9	21.4	7.5	66.5	Goal: Molecules of solute break away and mix with molecules of solvent.	Naive: No molecular motion initially. Focus on observable substances, or molecules themselves "dissolve."	1.0	19.5	1.9	58.1
5. Changes of states of matter	Goal: Air contains invisible water vapor, and water vapor in air condenses on cold objects.	Naive: No recognition of water vapor in air, or liquid water changes into air, and vice versa. Condensation is a reaction between heat and coldness.	2.0	5.8	0.5	30.8	Goal: Heating and cooling make molecules of substances move faster or slower, causing changes of state in terms of their arrangements and motion.	Naive: Heating and cooling make molecules themselves change (e.g., molecules "boil", "evaporate"), or molecules share in observable properties of substances (e.g., molecules begin to move when heated.)	3.0	27.8	1.2	41.4

*:Percentage of students who showed [illegible]

are hard, molecules of ice are frozen, and molecules are described as expanding, contracting, melting, evaporating, and so forth.

This study also indicates, however, that middle school students are capable of understanding some important aspects of the kinetic molecular theory. The students in this study were in an urban school district. Many were below grade level in reading and mathematics achievement; many came from lower socioeconomic status homes. The teachers were mostly nonscience majors and received only one day of inservice training before teaching the unit. Even under these less than ideal conditions, about 50% of the students achieved understanding of the scientific conceptions discussed earlier. We would conclude that these ideas are not beyond the intellectual reach of most sixth-grade students.

The curricular and instructional implications of this study are discussed in depth in other papers (Berkheimer et al., 1988b; Berkheimer et al., in press). Two points, however, are too important not to be mentioned here. First, this study and many others demonstrate that conceptual change research can and should play an essential role in curriculum development. Teaching materials based on conceptual change research can greatly enhance the effectiveness of even relatively poorly prepared teachers. Conversely, even the best prepared teachers face a long and difficult struggle if they wish to teach for meaningful understanding using currently available commercial materials.

Finally, this study points to an enormous gap in the current middle school science curriculum. A quick glance at almost any life science text reveals a large number of topics for which meaningful understanding depends on the scientific knowledge discussed in this paper (and often more): Osmosis and diffusion, photosynthesis, cellular respiration, digestion, transpiration, the

water cycle, ecological matter cycling, and so forth. Similar topics exist in earth science and physical science. This study indicates that most students do not know enough about the nature and constitution of matter to make sense of those topics, yet the issue is never addressed in depth in most science curricula. Omissions such as this play an important role in the present widespread and well-documented failure of our science education system.

References

Anderson, C.W. (1987). Incorporating recent research on learning into the process of science curriculum development. Commissioned paper for the Biological Sciences Curriculum Study.

Anderson, C.W. & Roth, K.J. (1989). Teaching for meaningful and self-regulated learning of science. In J. Brophy (Ed.), Advances in research on teaching : Vol. 1. Teaching for meaningful understanding and self-regulated learning (pp. 265-310). Greenwich, CT: JAI.

Anderson, C.W., Sheldon, T.H., & Dubay, J. (in press). The effects of instruction on college non-majors' conceptions of respiration and photosynthesis. Journal of Research in Science Teaching.

Anderson, C.W., & Smith, E.L. (1983, April). Children's conceptions of light and color: Developing the concept of unseen rays. Paper presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

Anderson, C.W., & Smith, E.L. (1987). Teaching science. In V. Richardson-Koehler (Ed.), Educator's handbook: A research perspective (pp. 84-111). New York: Longman.

Ben-Zvi, B., Eylon, B., & Libbarstein, J. (1982). Students versus chemistry: A study of student conceptions of structure and process. Rehovot, Israel: Weizmann Institute of Science.

Berger, C.F., Berkheimer, G.D., Neuberger, H.T., & Lewis, L.E., Jr. (1979). Houghton Mifflin Science: Teacher's edition, Level 6. Boston: Houghton Mifflin.

Berkheimer, G.D., Anderson, C.W., and Blakeslee, T.D. (1988a). Matter and molecules teacher's guide: Activity Book (Occasional Paper No. 122). East Lansing: Michigan State University, Institute for Research on Teaching.

Berkheimer, G.D., Anderson, C.W., & Blakeslee, T.D. (1988b, April). Using a new model of curriculum development to write a matter and molecules teaching unit. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Lake Ozark, Missouri.

Berkheimer, G.D., Anderson, C.W., Lee, O., & Blakeslee, T.D. (1988). Matter and molecules teacher's guide: Science Book (Occasional Paper No. 121). East Lansing: Michigan State University, Institute for Research on Teaching.

Berkheimer, G.D., Anderson, C.W., & Spees, S.T. (1990). Using conceptual change research to reason about curriculum. (Research Series No. 195). East Lansing: Michigan State University, Institute for Research on Teaching.

Blakeslee, T.D., Anderson, C.W., & Smith, E.L. (1987, April). Teaching strategies associated with conceptual change learning in science. Paper presented at the annual meeting of the American Educational Research Association, Washington, DC.

Eaton, J.F., Anderson, C.W., & Smith, E.L. (1984). Student misconceptions interfere with science learning: Case studies of fifth-grade students. Elementary School Journal, 84, 365-379.

Erickson, G. (1979). Children's conceptions of heat and temperature. Science Education, 63, 221-230.

Hesse, J.J., & Anderson, C.W. (1988, April). Students' conceptions of chemical change. Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA.

Hibbard, M.K., & Novak, J.D. (1975). Auto tutorial elementary school instruction as a method for study of children's concept learning: Particulate nature of matter. Science Education, 59, 559-570.

Minstrell, J. (1984). Teaching for the development of understanding of ideas: Forces on moving objects. In C.W. Anderson (Ed.), Observing science classrooms: Perspectives from research and practice (1984 yearbook of the Association for the Education of Teachers in Science. Columbus, OH: ERIC/SMEAC.

Novick, S., & Menis, J. (1976). A study of student perceptions of the mole concept. Journal of Chemical Education, 53, 720-722.

Novick, S., & Nussbaum, J. (1978). Junior high school pupils' understanding of the particulate nature of matter: An interview study. Science Education, 63, 273-281.

Novick, S.S., & Nussbaum, J. (1981). Pupils' understanding of the particulate nature of matter: A cross age study. Science Education, 65, 187-196.

Osborne, R.J., & Cosgrove, M.M. (1983). Children's conceptions of the changes of the state of matter. Journal of Research in Science Teaching, 20, 825-838.

Posner, G. J., Strike, K.A., Hewson, P.W., & Gertzog, W.A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66, 211-228.

Roth, K.J. (1985). The effects of science texts on students' misconceptions about food for plants. Unpublished doctoral dissertation, Michigan State University.

Roth, K.J., & Anderson, C.W. (1987). The power plant: Teacher's guide to photosynthesis (Occasional Paper No. 112). East Lansing: Michigan State University, Institute for Research on Teaching.

Toulmin, S. (1972). Human understanding. Princeton, NJ: Princeton University Press.

Vygotsky, L.S. (1962). Thought and language. Cambridge, MA: MIT Press.

Vygotsky, L.S. (1978). Mind in Society. Cambridge, MA: Harvard University Press.

APPENDIX A

THE 12 PRINCIPLES OF THE SMALL PARTICLE MODEL

HOUGHTON MIFFLIN SCIENCE

1. All matter is made up of particles.
2. Particles of matter are very small.
3. Particles of matter have spaces between them.
4. Particles of matter are in constant motion.
5. Particles of matter move faster when the matter is heated.
6. Particles of matter usually move farther apart when the matter is heated.
7. In the gas phase, the particles of matter are far apart and move freely.
8. In the solid phase, the particles of matter are packed together in a pattern and move within a small space.
9. In the liquid phase, the particles of matter are loosely clustered together and move about more than in solids.
10. Matter can be changed from solid to liquid and from liquid to solid.
11. Matter can be changed from liquid to gas and from gas to liquid.
12. Particles of matter attract each other.

From: Berger, Berkheimer, Neuberger, & Lewis, 1979, p. T-324.

APPENDIX B

Student Conceptions of Matter and Molecules

Issue	Goal Conception	Typical Naive Conception
Macroscopic level: Conceptions about observable substances and phenomena		
1. Definition of matter	1.a. Solids, liquids, and gases are matter, other things (e.g., heat, light) are not.	1.a. Gases and non-matter often incorrectly classified.
	b. Matter takes up space, non-matter does not.	b. Classification based on other properties (e.g., matter is some-thing you can see or feel).
2. Conservation of matter	2. Matter is conserved in all physical changes.	2. Matter not always conserved especially in changes involving gases. Words like "dissolve" and "evaporate" sometimes used as synonyms for "disappear."
3. Thermal expansion	3. Substances expand when heated.	3. Substances may "shrivel up" when heated; expansion of gases explained in terms of movement of air.
4. Nature of smells	4. Smells are gases, therefore matter, made of molecules, etc.	4. Smells considered ephemeral, not really matter.
5. Distribution of gases in space	5. Gases spread evenly through the spaces they occupy.	5. Distribution of gases is uneven before or after expansion or compression.
6. Compression of gases	6. Gases can be compressed.	6. Gases move from one region to another; no notion of compression or expansion.
7. Water vapor in air	7. Air contains invisible water vapor (humidity).	7. Water in air is visible (e.g., fog, "steam").
8. Condensation	8. Water vapor in air condenses on cold objects.	8. Condensate is "fog" or "breath"; or is formed by a reaction between heat and cold.
Molecular level: Conceptions about molecules and their nature		
9. Molecular constitution of matter	9. All matter is made of molecules, non-matter is not.	9. Material substances not described as molecular; non-matter described as molecules (e.g.,"heat molecules"); molecules are <u>in</u> substances.
10. Size of molecules	10. Molecules are too small to see, even with a microscope.	10. Molecules may be comparable in size to cells, dust specks, etc.
11. Constant motion	11. All molecules are constantly moving.	11. Molecules may sometimes be still, especially in solids.
12. Visibility of molecular motion	12. Molecular motion continues independently of observable movement.	12. Molecules simply share in observable movements of substances (e.g., convection currents); Molecules move in gases and liquids, not in solids.
13. Molecular explanation of dissolving	13. Molecules of solute break away and mix with molecules of solvent.	13. Focus on observable substances or molecules themselves "dissolve".
14. Effects of heat on molecular motion	14. The only effect of heat on substances is to make its molecules move faster.	14. Molecules themselves can be hot or cold.
15. Molecular explanation of thermal expansion	15. Increased motion moves molecules farther apart.	15. Molecules themselves expand.
16. Spaces between molecules	16. Gases consist of nothing except molecules with empty spaces between them.	16. Molecules have "air" or other things between them.
17. Molecular explanation of states of matter	17. States of matter are due to different arrangements and motions of molecules: -solids: vibrate in rigid array -liquids: random motion within liquid -gases: random motion, no limits	17. States of matter described only in terms of observable properties <u>or</u> properties of the state attributed to individual molecules (e.g., solid molecules are hard, liquid molecules are in drops, etc.).
18. Molecular explanation of changes of state	18. Heating and cooling cause changes of state by making molecules move faster or slower.	18. Heating and cooling make molecules "melt", "evaporate", etc.; <u>or</u> molecules begin to move when heated.
19. Molecular explanation of evaporation	19. Fast-moving molecules escape from liquid.	19. Molecules "evaporate" or disappear.

APPENDIX C

Tasks by Conceptions Chart for Kinetic Molecular Theory

Tasks	Conceptions																		
	Macroscopic								Molecular										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1. Describe/contrast/ classify matter vs. non-matter	x	x				x													
2. Describe states of matter	x	x				x		x		x	x	x				x	x		
3. Explain process and rate of dissolving		x	x	x						x	x	x	x	x			x		
4. Explain thermal expansion		x			x						x	x		x	x	x	x		
5. Explain expansion of gases		x						x								x	x		
6. Explain melting and freezing	x	x								x	x	x		x		x	x		
7. Explain evaporation and boiling	x	x	x			x			x	x	x	x		x		x	x	x	x
8. Explain smells	x	x	x	x			x			x	x	x				x	x	x	
9. Explain condensation	x	x	x	x		x			x	x	x	x		x		x	x	x	

APPENDIX D
PRE/POSTTEST

4/03/87

Period _____ Name _____

Date _____ Teacher _____

This test asks questions about topics that scientists deal with. We would like to know <u>your</u> ideas about these topics. Please answer each question as carefully and as thoroughly as you can. Do not worry about trying to finish the test, just do what you can in the time allowed. <u>Explain your own ideas</u>; good explanations are more important to us than "correct" scientific words.

1. Which of the following do you think is matter? (Circle yes or no or I don't know.)

air	yes	no	I don't know
light	yes	no	I don't know
helium	yes	no	I don't know
heat	yes	no	I don't know
steel	yes	no	I don't know
water	yes	no	I don't know
the smell of popcorn	yes	no	I don't know

Explain how you decided which things are matter and which are not.

_____

_____

_____

2. Which of the following do you think takes up space? (Circle yes or no or I don't know.)

air	yes	no	I don't know
light	yes	no	I don't know
helium	yes	no	I don't know
heat	yes	no	I don't know
steel	yes	no	I don't know
water	yes	no	I don't know
the smell of popcorn	yes	no	I don't know

Explain how you decided which things take up space and which do not.

_____

_____

_____

4/03/87

3. Choose solid, liquid, gas, or other for each thing below:

air	solid	liquid	gas	other
light	solid	liquid	gas	other
helium	solid	liquid	gas	other
heat	solid	liquid	gas	other
steel	solid	liquid	gas	other
water	solid	liquid	gas	other
the smell of popcorn	solid	liquid	gas	other

4. Have you ever heard of molecules? _____ If you answered yes, what do you think molecules are?

_____

_____

_____

5. Which of the following do you think is made of molecules? (Circle yes or no or I don't know.)

air	yes	no	I don't know
light	yes	no	I don't know
helium	yes	no	I don't know
heat	yes	no	I don't know
steel	yes	no	I don't know
water	yes	no	I don't know
the smell of popcorn	yes	no	I don't know

6. Do you think air is made of molecules?_____

If you answered yes, do you think that there is any space between the molecules?_____

If you answered yes, what do you think is between the molecules?_____

7. What do you think is bigger, a molecule or a speck of dust?

a. They are the same size.
b. The molecule. How many times bigger?_____
c. The speck of dust. How many times bigger?_____
d. I don't know.

8. John stirred some sugar into a glass of water. After awhile the sugar had all dissolved--the water was clear and John could not see any sugar.

   What happens to sugar when it dissolves in water?

   _____

   _____

   _____

   How do the molecules of water help this take place?

   _____

   _____

   _____

9. Choose one of the following:

   a. Sugar dissolves faster in hot water
   b. Sugar dissolves faster in cold water
   c. Sugar dissolves about the same in hot and cold water
   d. I don't know

   Explain your answer.

   _____

   _____

   _____

10. A solid iron ball exactly 3 inches across was heated on the stove. If it did not melt, would you expect it to

    a. be larger
    b. be smaller
    c. stay the same size
    d. I don't know

    Explain your answer.

    _____

    _____

    _____

11. When a piece of metal is heated:

a. the number of molecules increase.
b. molecules expand or get larger.
c. molecules stay the same size but move farther apart.
d. molecules contract or get smaller.
e. I don't know.

12. How do you think the molecules of hot water are different from the molecules of cold water? Circle all answers that you think are correct.

a. the molecules are larger in hot water.
b. the molecules are larger in cold water.
c. the molecules move faster in hot water.
d. the molecules are warmer in hot water.
e. the molecules are the same, but there is more heat in the hot water.
f. I don't know.

13. These two bottles were put into the refrigerator until they were cold. Balloons were placed over the rims of the bottles. A student took one bottle out of the refrigerator and warmed it with her hands. Which bottle did she warm? Circle your choice.

A.

B.

Explain your answer.

14. You cut up an onion into small pieces. You notice the smell in a few seconds. Explain what you think the smell is made of?

Explain how it reached you. Talk about molecules, if you can.

15. By using a bicycle pump you force 8 cups of air into a tire that is only 2 cups in volume. The tire gets only a little bit bigger.

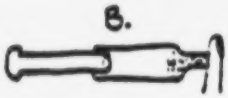
Explain how this is possible.

16. The hole of a plastic syringe full of air is plugged up.

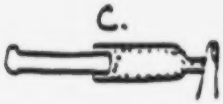
The plunger is pulled back. Which of the four diagrams best shows how the air is distributed?

A.

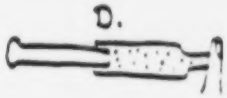
B.



C.



D.



Explain your choice.

17. Do you think the molecules are moving in <u>windy air</u>?
    a. Yes, they are moving.
    b. No, they are not moving.
    c. I don't know.

    Do you think the molecules are moving in <u>still air</u>?
    a. Yes, they are moving.
    b. No, they are not moving.
    c. I don't know.

    Do you think the molecules are moving in a <u>rock</u>?
    a. Yes, they are moving.
    b. No, they are not moving.
    c. I don't know.

    If you said the molecules were moving in any of the examples above, do you think they will ever stop moving? _____

    Explain.

    _____

    _____

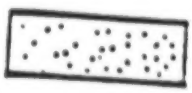
    _____

18. Choose the picture that shows the arrangement of molecules in each substance. You may use each picture more than once, if you need to.

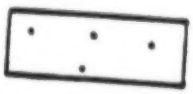
    Iron _____

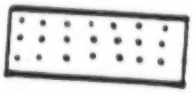
    Water _____

    Air _____

    a. 

    b.

    c. 

    d. 

    e.

19. A piece of ice is melted to liquid water. How would the weight of the water compare to the weight of the ice?

a. The water would weigh <u>less</u> than the ice.
b. The water would weigh <u>the same</u> as the ice.
c. The water would weigh <u>more</u> than the ice.
d. I'm not sure.

Explain your answer.

_____

_____

_____

20. Explain in your own words, why heating a solid makes it melt. Explain in terms of molecules of the solid, if you can.

_____

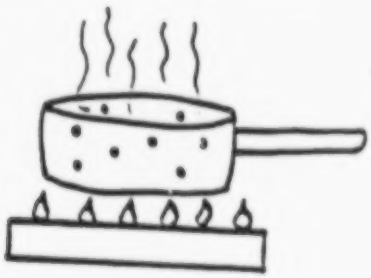
_____

_____

21. What happens to the molecules of water when the water freezes?

a. Molecules of water become cold and hard.
b. Water molecules change into ice molecules.
c. Molecules of water slow down and fit together in a pattern.
d. Molecules of water get smaller.
e. I don't know.

22. When water boils, bubbles rise to the surface of the water. What do you think is inside the bubbles?_____



Explain in your own words why heating makes the water boil. Explain in terms of molecules, if you can.

_____

_____

_____

23. You leave a glass full of water on the counter where nobody touches it. A few days later, the water level is lower than before. Where do you think the water has gone?

_____

Explain how this happens, in terms of molecules if you can.

_____

_____

_____

24. You and a friend are sitting in a car on a cold winter day. You talk for awhile, then you notice that the windows have fogged up.

What do you think the fog is?

_____

Why did the fog form on the windows instead of, say, on your face?

_____

_____

_____

Explain how the fog formed.

_____

_____

_____

25. You take a can of soft drink out of the refrigerator and let it stand for 15 minutes. The outside of the can becomes wet.

Where has the water on the outside of the can come from?

a. The water in the soft drink seeps through the can.
b. The coldness causes oxygen and hydrogen in the air to form water on the can.
c. Water in the air forms drops on the cold can.
d. The coldness comes through the can and turns into drops of water.
e. I don't know.

26. When we say the air is humid, what do we mean?
Explain in terms of molecules, if you can.

_____

_____

_____

APPENDIX E - Clinical Interview Protocol

TASK 1: Describe, contrast, and classify the three states of matter.

Situation:
Set up rock, water and plastic bag of air in front of the student.

Materials:
Rock or metal, Water, Plastic bag of air
Sheet with a list of things
Pencil and paper for drawings

	Questions	Commentary	Goal Conceptions
Task 1-1 States of matter	O: Can you tell me how these three things are different? P1: Do you know what the three states of matter are? (If the student doesn't know) Have you ever heard of solids, liquids, and gases? P2: What state of matter is rock? P3: What state of matter is water? P4: What state of matter is air? P5: How do you decide whether something is a solid or liquid? P6: How do you decide whether something is a liquid or gas?		1,4,9
Task 1-2 Molecular constitution of matter	O: Can you think of any way that these three things are similar? P1: Have you ever heard of molecules? P2: What are they? P3: How big are they? How does their size compare to the size of a speck of dust? P4: Can you think of something that's not made of molecules?		9,10,11,12 16,17

Task 1-3	Questions	Commentary	Goal Conceptions
Nature of gas (air)	O: What is air? P1: (If the student says there is nothing in the air) Wave your arm in the air. Do you feel anything? Is anything striking your arm? What is it? P2: Suppose you are able to see air with magic eyeglasses. What is air made of? (What is in the air?) P3: Draw a picture of what you would see? P4: (If the student draws dots, waves, etc.) What are these dots (waves, etc.)? Are they all the same? What is between them? Are they moving? If so, are they always moving? P5: (If student mentions molecules) Is air a mixture? What does that mean? Is air made of different molecules?	whether students think in terms of empty spaces and constant motion of molecules (waves, chunks, etc.), and Purposes: To determine (1) students' conceptions of air, (2) student's microscopic view of gases (air), liquids, and solids, (3) (4) whether students understand that the empty space and motion vary in solids, liquids, and gases (air).	9,10,11,12 16,17
Task 1-4 Nature of liquid (water)	O: Suppose you can see water with magic eyeglasses. What is water made of? P1: Draw a picture of what you would see. P2: (If the student draws dots, waves, etc.) What are these dots (waves, etc.)? Are they all the same? What is between them? Are they moving? If so, are they always moving?		
Task 1-5 Nature of solid	O: Another student told me that a rock is made of very very, very small particles or pieces that are always jiggling back and forth. What do you think of that? P1: (If student agrees and/or mentions molecules) Are the molecules of a rock still? P2: Suppose you can see rock through magic eyeglasses. Draw a picture of what you would see. P3: (If student draws dots) What are these dots? Are they all the same? Is there any space between them?		

Task 1-6	Questions	Commentary	Goal Conceptions
Comparison of three states of matter	O: Now you have drawings of air, water, and rock. What is the difference among these substances from your drawings? P1: (If the student mentioned that there is space between... in the drawings) Is the space the same in all states? (If the student says no) Which has the largest space? Which has the smallest space? P2: (If the student mentioned that they are moving) Is the movement the same in all states? (If the student says no) Which has the most movement? Which has the least movement?		9,10,11,12 16,17

TASK 2: Explain and contrast Compression of Cases and Liquids

Situation:

Student will cover the end of the syringe with his/her finger and push down on the plunger first with the syringe filled with air and second with the syringe filled with water.

Materials:

Syringe (2)
Water and air
Drawings of syringe in normal state and when compressed

Task 2-1	Questions	Commentary	Goal Conceptions
Compression of gas	O: What do you think will happen if you push down on the plunger? P1: What do you notice when you push on the plunger? P2: Explain why the plunger can be pushed in most of the way, (2) but not all of the way. P3: Draw a picture of the air before and after it is compressed in the syringe. (If the student cannot respond to this question, show him/her the drawings from the test.) P4: Compare the drawings when the air is compressed and not compressed. P5: Name another example of a gas. P6: What will happen if you use another gas in the syringe?	**Purposes:** To determine whether students (1) know that air (gases) is compressible and water (liquids) is not in a syringe, and (2) can relate compressibility of gases to the relative size of empty spaces between gases (air) and liquids (water). **What we want to know:** Can students (1) explain (on a microscopic level in terms of space and distribution) why air (gases) is compressible and water (liquid) is not, and (2) generalize from these examples to all gases and liquids.	5,6,9,16,17

Task 2-2	Questions	Commentary	Goal Conceptions
	O: What do you think will happen with water in the syringe?		5,6,9,16,17
Compression of liquid	P1: Why can't you compress water? (If student has difficulty, ask) You pushed on the plunger of the syringe with air in it and then with water in it. Why can you compress air but not water?		
	P2: Name another example of liquid.		
	P3: What will happen if you use that liquid in the syringe?		

Task 2-3

Comparison of gas vs. liquid	O: You pushed on the plunger in the syringe with air in it and then with water in it.	
	P1: Why can you compress air but not water?	

Task 3: Explain Changes of States of Matter

Situations:

Melting ice: Leave ice cubes melting in the plastic cup.
Boiling water: boil water in the beaker on the plate.
Condensing water: Pop can and glass plate above boiling water
Evaporating alcohol: Place drops of alcohol on the slide.
Smell of perfume: Take top off of perfume container

Task 3-1	Questions	Commentary	Goal Conceptions
Melting ice	O: What's happening to the ice cubes?		2,9,11,12 14,15,17,18
	P1: What state of matter is ice? What state of matter is water?		
	P2: How does ice change into water?		
	P3: (If student has mentioned molecules) Can you explain what's happening to the molecules?		
	P4: Does ice have to be heated to melt? Why?		
	P5: In which state do molecules move more freely?		
	P6: In which state are they farther apart?		

Task 3-2			
Boiling	O: What's happening to the water? Describe what you see.		2,7,9,11 14,15,17,18
	P1: If we leave water boiling, what happens to the amount of water in the beaker?		
	P2: Why is the amount of water lower?		
	P3: Where is the water going?		
	P3: (If student mentions bubbles) Is there anything inside the bubbles? What?		
	P4: (If the student mentions "air") Do you think the air in the bubbles is the same as the air in this room?		
	or (If the student mentions "steam") What do you mean by "steam"? What state of matter is steam?		
	P5: How does the water change from liquid to gas? Can you explain in terms of molecules?		
	P6: Which has more space between molecules, liquid or gas?		

Task 3-3	Questions	Commentary	Goal Conceptions
condensing on glass plate	O: What is happening on the plate? P1: Where does the water come from? P2: (If the student mentions "air") How does air change to water? or (If the student mentions "steam") How does steam change from gas to liquid? Can you explain in terms of molecules? P3: Which state has more space between molecules, gas or liquid? P4: In which state do molecules move more freely? P5: In which state do molecules move farther apart?		2,7,8,9 14,15,17,18,19
Task 3-4 Evaporation	O: What do you see happening here? P1: Where did the alcohol go? P2: Did it disappear? If so, is it gone forever? Does it still exist? P3: How does the alcohol evaporate? P4: Is alcohol made of molecules? What kind? P5: What's happening to the alcohol molecules? P6: Would anything happen differently if we heated the glass and alcohol?		2,7,9,10 11,12,17,19
Task 3-5 Smell	O: Can you smell the perfume? P1: What is the smell made of? P2: How did the smell of perfume get from the glass to your nose? P3: Can you explain in terms of molecules? P4: Molecules of what? Where did they come from? P5: If we put a top on the perfume, would you still be able to smell it? Why or why not?		

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TASK 4: Explain Pure Substance vs. Mixture and Process and Rate of Dissolving

Situations:
Dissolve Epsom salts (in tea bag) in water.

Materials:
Epson salts, Tea bags, Cups, cold water

Task 4-1	Questions	Commentary	Goal Conceptions
Dissolving Epsom salts (or sugar)	O: What is happening to the Epsom salts (or sugar)? P1: (If the student mentions "dissolves") What do you mean by "dissolves"? P2: How does it get out of the tea bag? Can you explain in terms of molecules? P3: If we leave Epsom salts and water sitting for one day, what will happen? Will Epsom salts be all over or in one place? Will Epsom salts sink to the bottom? Why or why not? Can you explain in terms of molecules? P4: If we put a tea bag of Epsom salts in a cup of hot water and a cup of cold water, which would dissolve faster? Why? Can you explain in terms of molecules? P5: Is the Epsom salts and water a mixture or a pure substance? P6: Can you explain why?		2,9,10,11,12 13,14

Task 5: Explain Thermal Expansion of Gas and Solid

Situations:

Put the balloon on the rim of the cold bottle, and then warm it with hands (bottle on its side).
Have the student put the ball through the ring, heat the ball, and have the student try to pull the ball back through the ring.

Materials:

Balloon, Bottle,
Ball, Ring, Hot Plate

Task 5-1	Questions	Commentary	Goal Conceptions
Thermal expansion of gas	O: What will happen to the balloon after we put our hands on the bottle? P1: What happens to the balloon? Why? P2: What caused the balloon to get bigger? P3: (If the student responds "Hot air rises," then turn the bottle upside down.) Can you explain why the balloon stays the same? Can you explain in terms of molecules? P4: Does the molecule motion or size change when the bottle is warmed? If so, in what way? P5: Does the number of molecules change as the bottle is warmed? P6: Is there a change in the space between molecules as the bottle is warmed? P7: Were the molecules of air in the bottle moving before we started to warm the bottle? P8: Do molecules move faster, when the bottle is cold or heated? P9: Do molecules move farther apart, when the bottle is cold or heated?	Purposes: To determine how students explain thermal expansion of gases and solids. What we want to know: Macroscopic: (1) Do students think that solids and gases expand or shrink when heated, and (2) do students think in terms of hot air rising or expanding in all directions when heated? Microscopic: Can students explain thermal expansion in terms of molecular motion and empty spaces?	3,9,11,12 14,15,16
Task 5-2 Thermal expansion of solid	O: The ball goes through the ring now (unheated). What will happen if we heat the ball? P1: Why can't we pull the ball through the ring after heating? Can you explain in terms of molecules?		

Task 5	Questions	Commentary	Goal Conceptions
(cont.)	P2: Does the molecule motion or size change when the ball is heated?		3,9,11,12 14,15,16
	P3: Does the number of molecules change as the ball is heated?		
	P4: Is there a change in the space between molecules as the ball is heated?		
	P5: Were the molecules of the ball moving before we started to heat it?		
	P6: Do molecules move faster when the ball is heated or cold?		
	P7: Do molecules move farther apart when the ball is heated or cold?		

APPENDIX F

CLINICAL INTERVIEW ANALYSIS FORM

Student #_____

Before/After Instruction

Source: c.i./test

(clinical interview)
(paper-and-pencil test)

Key: G = Goal Conception
N = Naive Conception
M = Mixed (goal + naive)
A = Ambiguous/Inconclusive

Tasks-by-Conceptions Chart for Kinetic Molecular Theory

Tasks | Conceptions

Macroscopic level | Molecular level

Assessment		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	comments
1. Matter vs. non-matter	a. describe & contrast																				
	b. classify examples																				
2. Compare/ contrasst states of matter	a. composition																				
	b. dif. betwn. s/l/g																				
	c. examples of s/l/g																				

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	comments
3. Explain dissolving	a. sugar b. hot/cold water																				
4. Explain thermal expansion	a. balloon/bottle b. ball/ring																				
5. Explain expansion & compression of gases	a. syringe b. syringe: air vs. water c. bike tire																				
6. Explain melting and freezing	a. ice melting b. water freezing																				
7. Explain evaporation & boiling	a. boiling b. steam & bubble c. alcohol d. cup of water																				
8. Explain smells	a. perfume b. onion																				
9. Explain condensation	a. pop can b. ice water cup c. car window																				